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Isospin transport phenomena and odd-even staggering in ^{84}Kr+^{112,124}Sn collisions at 35 AMeV

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Abstract

Experimental results concerning isospin transport phenomena and odd-even staggering in Z and N distributions are presented. Data refer to ^{84}Kr+^{112,124}Sn collisions at 35AMeV and they were collected with a high resolution FAZIA telescope, able to isotopically resolve ions up to $Z \sim 20$. Evidences of isospin diffusion and drift obtained from the $< N > /Z$ behaviour of the detected fragments are discussed. The odd-even staggering both in Z and N is compared with experimental data available in literature, finding that it shows a common trend in different reaction types.

1 Introduction

In recent years many theoretical and experimental works (*e.g.* [1]- [3] and references therein) aimed at the investigation of the density dependence of the symmetry energy term $S(\rho)$ of the nuclear equation of state for asymmetric nuclear matter. This dependence can be inferred from the study of isospin effects on many observables related to the isotopic composition of the decay products. Such effects arise because neutrons and protons are subject to different forces, whose strength depends on the symmetry energy term. In particular, one expects effects driven by the isospin gradient between target and projectile (isospin diffusion), sensitive to the symmetry energy itself, according to the term $S(\rho)\nabla I$ (where $I = \frac{N-Z}{A}$), and effects driven by the density gradient $\nabla\rho$ between the Quasi-Projectile (QP)/Quasi-Target (QT) region (at normal density) and the more diluted neck zone (isospin drift process); in this last case the effect is sensitive to the derivative of the symmetry energy, according to the term $\frac{\partial S(\rho)}{\partial\rho} I \nabla\rho$ [1].

The isospin transport phenomenon is still an open problem in dissipative heavy ion collisions at intermediate energies and it is a challenge from the experimental point of view, because it requires isotopic identification in a wide range of Z. Moreover, information on the symmetry energy term is generally obtained by comparing experimental data with the predictions of theoretical models. It is therefore important that the afterburner (*e.g.* a statistical code like GEMINI [4]), which is applied to primary variables (see an example in [3]), well reproduces the decay of primary fragments in all its aspects, including the staggering effect. In literature such a phenomenon is widely described for the Z distribution, in different kind of reactions, from low energy (*e.g.* [5]) to intermediate energies (*e.g.* [6]- [7] and references therein) and up to spallation and fragmentation at relativistic energies (*e.g.* [8] and references therein). In [6] (in a small range) the staggering in the N distribution is discussed too. Although the origin of the staggering phenomenon is not completely understood, it is generally ascribed to the restoration of structure effects, such as the pairing interaction, in the last step(s) of the decay. At present, to our knowledge, the available statistical codes are able to reproduce only some gross features of the process. In any case, from the experimental point of view, an accurate investigation of the staggering phenomenon in Z and N requires isotopic resolution in a wide range of Z.

In order to meet the requirements in terms of isotopic identification needed for isospin physics, the FAZIA Collaboration started its R&D phase in 2006, aiming at the design and construction of new generation Si-Si-CsI(Tl) telescopes, with improved isotopic resolution (up to $Z \sim 23$ for ions punching through the first silicon layer) and reduced identification thresholds (thanks to a refined use of digital Pulse Shape Analysis for particles stopped in the first silicon layer). The main achievements and technical solutions are summarized in a recent review paper [9] (and references therein).

2 Results

2.1 Isospin transport

Taking advantage of a test run for a prototype performed in 2011 at LNS in Catania (Italy) and exploiting the good isotopic identification of the telescope, the FAZIA Collaboration investigated the isospin transport phenomenon [10] and the odd-even staggering in Z and N distribution [11], although in an inclusive way. A ^{84}Kr beam (N/Z=1.33) at 35AMeV was used, with two different targets, a n-poor ^{112}Sn (N/Z=1.24) and a n-rich ^{124}Sn (N/Z=1.48). The detector was located at $4.8° \leq \vartheta \leq 6°$, just beyond the grazing angle of both reactions and it was able to detect only fragments forward emitted in the centre of mass, coming from the QP phase space, i.e. the QP residues (Z $\geq$ 20) or its fission fragments, evaporated particles and neck emissions (close to the centre of mass), with a negligible contamination due to QT, as it can be inferred from figure 2 of [10]. As a consequence, the fact that the $< N > /Z$ of fragments detected in the reaction with the n-rich target (open circles in fig. 1) is sistematically higher than in the case of the n-poor one (full circles in fig. 1) can be interpreted as an evidence of isospin diffusion between target and projectile.

The velocity dependence of the $< N > /Z$ of the detected fragments shows that for heavy fragments (right part of fig. 2) the average isospin is almost independent of the lab velocity, as expected, because they mainly come from a single mechanism, *i.e.* the QP fission. On the contrary, as

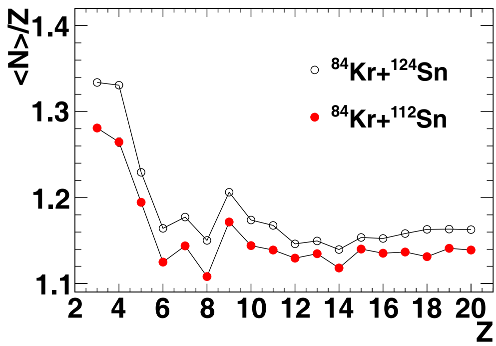

Figure 1: $< N > /Z$ of the detected fragments as a function of their charge for the reactions ^{84}Kr+^{112}Sn (full circles) and ^{84}Kr+^{124}Sn (open circles).

depicted in the left part of fig. 2, light fragments with velocity close to the centre of mass show a higher $< N > /Z$ with respect to those close to the QP velocity. Since light fragments come from two different mechanisms, *i.e.* neck emission and QP evaporation, we interpret this phenomenon as a possible evidence of isospin drift, with a migration of isospin from the region of QP/QT (at normal density) towards the more diluted neck zone.

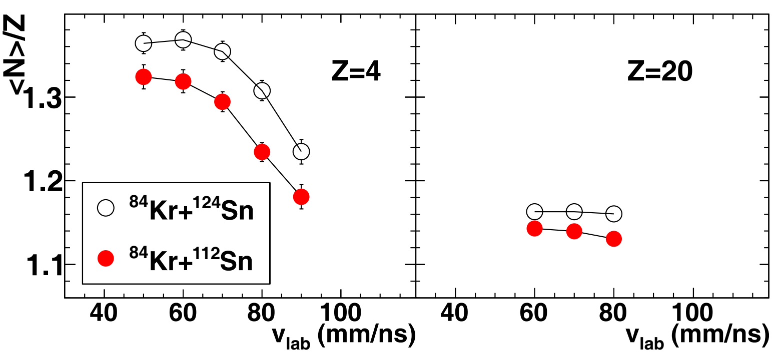

Figure 2: $< N > /Z$ of the detected fragments as a function of their lab velocity for the reactions ^{84}Kr+^{112}Sn (full circles) and ^{84}Kr+^{124}Sn (open circles); left part: Z=4; right part: Z=20.

2.2 Z and N staggering

Concerning the staggering, in order to perform quantitative comparisons in different data sets, we used a slight modification of the parameter $\delta(P)$ of [5], where P=Z or N. This quantity is positive if there is positive staggering (*i.e.* the yields associated to even values of N or Z are greater than those for odd Z or N), null if there is no staggering, and negative in case of anti-staggering. As it can be appreciated from fig. 3, in which the δ quantity is presented for the Z (left side) and N (right side) distributions, for the two systems (open points: n-rich target; full points: n-poor one), the N staggering is wider than the Z staggering. Moreover, the Z staggering is slightly greater for the n-poor case, while the N staggering is more similar for the two systems. Finally, the staggering amplitude tends to decrease when the size of the fragments increases, with some bumps, for example around Z=30 (as already seen in [7] for a similar system).

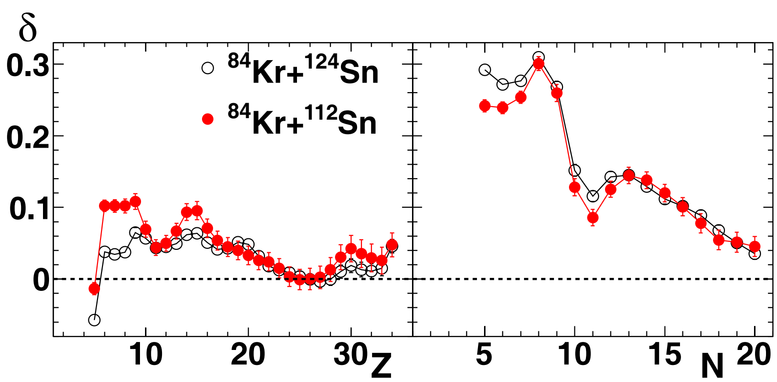

Figure 3: δ parameter for Z (left side) and N (right side) distributions for the reactions ^{84}Kr+^{112}Sn (full circles) and ^{84}Kr+^{124}Sn (open circles).

In order to put into evidence general trends, we have calculated the average δ in different intervals corresponding to common ranges in some sets of data available in literature, both for Z and (when possible) for N distributions. The obtained systematics is summarized in fig. 4 for the Z (left side) and the N distribution (right side) as a function of the isospin of the entrance channel. Each point corresponds to a different system (each one identified by a different letter) and/or (for FAZIA data only) to a different range in which the average δ is calculated, as explained in the caption of the figure. Systems belonging to different reaction classes are compared: from low-medium energy reactions (letters **a,b,c,d,e,i**) up to reactions of spallation and fragmentation at relativistic energies (**f,g,h**). Looking at this

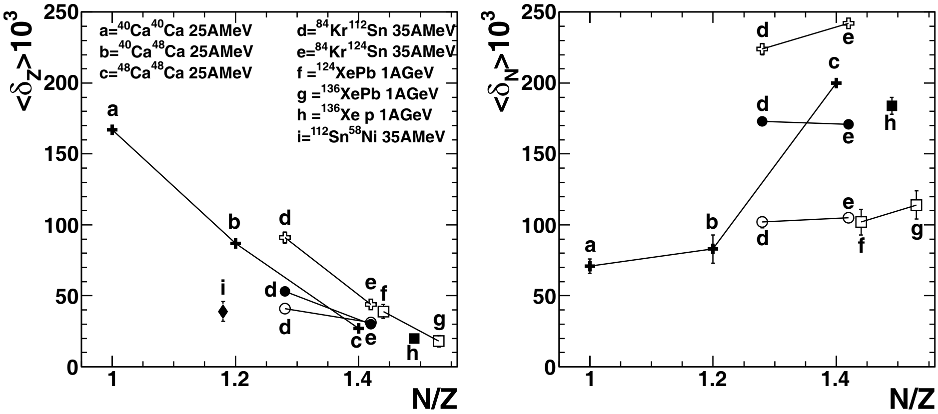

Figure 4: Average δ parameter for Z (left side) and N (right side) distributions for different systems taken from literature as a function of the isospin of the total system. Letters **a,b,c** refer to [6]; **d,e** to [11]; **f,g** to [12]; **h** to [8]; **i** to [7]. Left side: full and open crosses correspond to the average done in the range Z=6-11; open circles and open squares correspond to the average in the interval Z=12-34; full circles, full squares and full diamonds correspond to the range Z=5-34. Right side: full and open crosses correspond to the average done in the range N=6-11; open circles and open squares correspond to the average in the interval N=10-20; full circles and full squares correspond to the range N=5-20.

picture, it is important to keep in mind that the value on the abscissa, *i.e.* the isospin of the entrance channel, does not necessarily correspond to the N/Z of the emitting source. For example, the correspondence is exact for the system ^{136}Xe+p 1AGeV (**h**, from [8]) or almost exact for the symmetric system $^{40}Ca +^{40} Ca$ (**a**, from [6]), but it is certainly not correct for FAZIA data (letters **d,e**). In any case, taking into account this caveat, this picture shows that data belonging to different regimes and reaction mechanisms have a common trend. This observation confirms the fact that the staggering phenomenon is weakly dependent on the reaction mechanism and it is a last step(s) effect. Another observation which arises from this picture is the fact that while the Z staggering decreases when the isospin of the system increases, the N staggering shows a less evident dependence on the N/Z of the total system.

3 Summary and perspectives

Some experimental results obtained by the FAZIA Collaboration in an inclusive experiment on the systems ^{84}Kr+^{112,124}Sn at 35AMeV and concerning the isospin transport phenomena and the odd-even staggering both in Z and N distributions have been presented. In particular, evidence of isospin diffusion relies on the fact that the $< N > /Z$ of fragments belonging to the QP phase space is systematically higher when the target is n-rich than when the target is n-poor. Evidence of isospin drift can be deduced from the fact that the $< N > /Z$ of light fragments is higher when their velocity is closer to the centre of mass, i.e. when they probably come from the neck emissions. Concerning the staggering topic, the comparison of data available in literature corresponding to different reaction mechanisms (from low-medium beam energies up to relativistic collisions) points to a common trend as a function of the isospin of the total system. This observation supports the idea that the staggering phenomenon is mainly a last step(s) effect, weakly dependent on the particular reaction mechanism.

The FAZIA experimental program foresees new measurements on the discussed topics with more detectors (up to 12 blocks of 16 telescopes coupled to INDRA); in this way it will be possible to study the isospin transport phenomena for different classes of events. Moreover, taking advantage of the correlation technique, we will attempt the reconstruction of the last but one step of the decay, as tried in [13], in order to put into evidence the role of the last evaporation phase in building up the final yields.

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